Final Report

Project: NASA AISRP NNG04GP89G

Title: Block-Adaptive Parallel Implicit Methods for Semirelativistic Multifluid Hall-MHD

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This project had several goals:

1. Implementation of Hall MHD in the block-adaptive 3D MHD code BATS-R-US.
2. Development and implementation of an implicit time-stepping algorithm to solve the equations of Hall MHD in BATS-R-US
3. Implementation and application of multifluid Hall MHD in BATS-R-US.

All three goals have been achieved. Below we summarize our main accomplishments in more detail.

Hall MHD

We implemented, tested and validated the Hall MHD term in BATS-R-US. The implementation ensures high computational performance, excellent parallel scaling and it is compatible with the general philosophy of block-adaptive AMR.

In Hall MHD the electric field is modified from the resistive MHD expression by including the Hall term, jxB/n (j=electric current density, B=magnetic field, n=electron concentration). This seemingly simple modification is quite challenging to implement in a conservative, accurate and efficient manner. There are at least two challenges:

(i) there is a second order spatial derivative that cannot be rewritten into a simple Laplace operator, and

(ii) the maximum wave speed of the equation increases from the fast magnetosonic wave to the whistler wave speed that is approximately inversely proportional to the wave length.

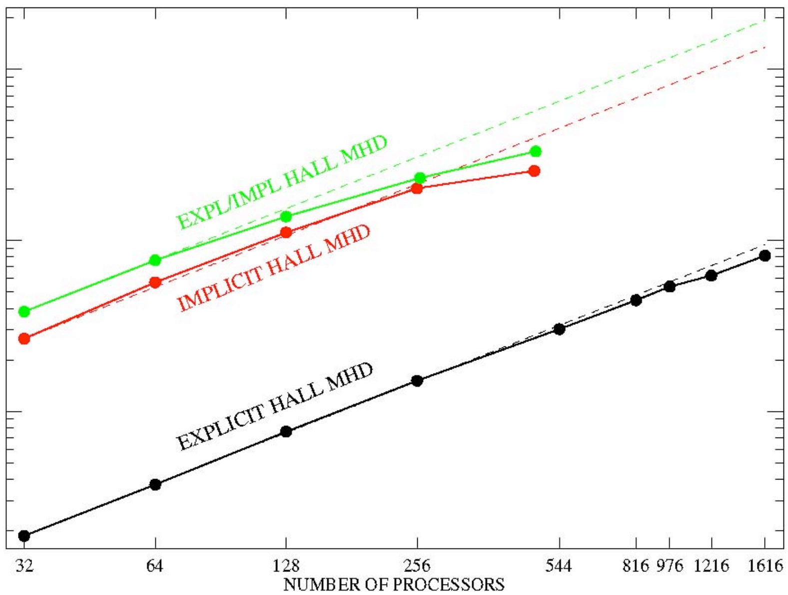
The first problem is especially difficult because of the adaptive block structure of the BATSRUS code. It took a lot of careful derivation and algorithmic development to obtain a spatially second order accurate discretization at resolution changes.

The second problem is also very important, because it limits the maximum explicit time step to extremely small values. It was solved by using a very efficient implicit time-stepping method.

Implicit Hall MHD

We developed a second order accurate Hall MHD scheme for block adaptive Cartesian or general structured grids using both explicit and implicit time integration. For steady state solutions the explicit scheme can be used in combination with local time stepping. Care should be taken to use symmetric type limiters (like MC) instead of asymmetric limiters (like minmod or super-bee) to achieve second order accuracy in smooth regions. For time accurate runs the implicit scheme is much more efficient than the explicit scheme if the whistler wave speed is dominant. The preconditioner has to take into account the terms responsible for the whistler wave.

Using the implicit scheme the Hall MHD simulation ran about 3-4 times slower than the classical MHD simulation, which is quite reasonable given the stiffness of the Hall MHD equations due to the whistler wave. The efficiency and good parallel scaling of our Hall MHD scheme enables us to do steady state and time accurate simulations in 3D. We have already used the Hall MHD code to simulate Titan's interaction with the surrounding plasma.



Speedup of the explicit, implicit and explicit/implicit time stepping schemes for a fixed size magnetosphere problem.

This steady state simulation uses a spherical grid with logarithmic stretching in the radial direction. The Hall MHD results match the values measured by the Cassini satellite significantly better than the results obtained with classical MHD simulations. We plan to use the Hall MHD code to study many space physics problems in the future.

Multifluid Hall MHD

We developed a new, conservative method to solve the multifluid Hall MHD equations and implemented the method in BATS-R-US and the Space Weather Modeling Framework (SWMF). The method has been applied to Saturn and Mars, two high priority target of NASA. The new method has been used to accomplish new scientific results that were published in peer-reviewed journals and presented at national and international conferences.

Publications

1. G. Toth, Y. Ma and t.I. Gombosi, Hall Magnetohydrodynamics on Block Adaptive Grids*, J. Comp. Phys.*, submitted, 2008.

2. I. V. Sokolov, K. G. Powell, T. I. Gombosi, aand I. I. Roussev, A TVD Principle and Conservative TVD Schemes for Adaptive Cartesian Grids, *J. Comp. Phys.*, *220*, 1-5, 2006.
3. G. Toth, D.L. De Zeeuw, T.I. Gombosi, and K.G. Powell, A parallel explicit/implicit time stepping scheme on block-adaptive grids, *J. Comput. Phys.*, *217*, 722-758, 2006.
4. G. Toth, I. V. Sokolov, T. I. Gombosi, D, R. Chesney, C. R. Clauer, D. L. De Zeeuw, K. C. Hansen, K. J. Kane, W. B. Manchester, R. C. Oehmke, K. G. Powell, A. J. Ridley, I. I. Roussev, Q. F. Stout, O. Volberg, R. A. Wolf, S. Sazykin, A. Chan, and Bin Yu, Space Weather Modeling Framework: A new tool for the space science community*, J. Geophys. Res.*, *110*, A12226, doi:10.1029/2005JA011126, 2005.
5. Y. Ma, A. F Nagy, T. E. Cravens, I. V Sokolov, J. Clark, and K. C. Hansen, 3D Global MHD model Prediction of the first close flyby of Titan by Cassini, *Geophys. Res. Lett., 31*, 10.1029/2004GL021215, 2004.

Invited Presentations

1. T.I. Gombosi, Simulating everything under the Sun: Coupled model of solar and heliospheric disturbances, Earth-Sun System Exploration Conference, Kona, Hawaii, January 14-18, 2008.
6. T.I. Gombosi, G. Toth, I. Sokolov, D.L. De Zeeuw, O. Cohen, A. Glocer, Y. Ma, K.C. Hansen, W.B. Manchester, A.J. Ridley, K.G. Powell and Q.F. Stout, Adventures with the Space Weather Modeling Framework, Space Weather Workshop, Boulder, CO, April 24-27, 2007.
7. Gombosi, T.I., Glocer, A., Toth, G., Hansen, K.C., Ridley, A.J., Modeling ionospheric outflows with the Space Weather Modeling Framework, 2007 EGU
8. T.I. Gombosi, G. Toth, I.V. Sokolov, D.L. De Zeeuw, A.J. Ridley, Coupled Modeling with the Space Weather Modeling Framework, Challenges to Modeling the Sun-Earth System (Huntsville 2006 Workshop), Nashville,
9. T.I. Gombosi, End-to-end space weather simulations with SWMF, Space Weather Week, Boulder, CO, April 25-28, 2006.
10. T. I. Gombosi, G. Toth, I. V. Sokolov, W. B. Manchester, A. J. Ridley, I. I. Roussev, D. L. De Zeeuw, K. C. Hansen, K. G. Powell, and Q. F. Stout, Halloween Storm Simulations with the Space Weather Modeling Framework, 44th AIAA Aerospace Sciences Meeting, Reno, Nevada, January 9-12, 2006.
11. T.I. Gombosi, Severe weather in space, NASA ESTO Technology Conference, Adelphi, MD, June 28-30, 2005.
12. T.I. Gombosi, D.L. De Zeeuw, I.V. Sokolov, G. Tóth, A.J. Ridley, K.C. Hansen, W.B. Manchester, I.I. Roussev, C.R. Clauer, K.G. Powell, Q.F. Stout, B. van Leer, P.L. Roe, Parallel, Adaptive, Coupled Plasma Simulations, Multiscale Processes in Fusion Plasmas, IPAM UCLA, Los Angeles, CA, January, 2005.

Contributed Talks

1. A. Glocer, G. T{\'o}th, T.I. Gombosi, Modeling Ionospheric Outflow During a Geomagnetic Storm, 2007 Fall AGU Meeting, San Francisco, CA, December 10-14, 2007.

2. G. Toth, A. Glocer, M.-C. Fok, T.I. Gombosi, Integration of the Radiation Belt Environment Model Into the Space Weather Modeling Framework, 2007 Fall AGU Meeting, San Francisco, CA, December 10-14, 2007.

3. G. Toth, Y. Ma, T.I. Gombosi, M.M. Kuznetsova, Comparison of Hall MHD and the non-gyrotropic resistivity model in the global magnetohydrodynamic code BATSRUS, 2007 Spring AGU Meeting, Acapulco, Mexico, May 21-25, 2007.

4. Toth, G., Gombosi, T.I., Sokolov, I.V., De Zeeuw, D.L., Ridley, A.J., Manchester, W.B., Ma, Y., Validation of the Space Weather Modeling Framework, 2007 EGU General Assembly, Vienna, Austria, April 16-20, 2007.

5. Toth, G., Ma, Y., Gombosi, T.I., Sokolov, I.V., Hall MHD Simulations on Block Adaptive Grids, 2006 Fall AGU Meeting, San Francisco, CA, December 11-15, 2006.

6. Kuznetsova, M.M., Hesse, M., Rastaetter, L., Gombosi, T., De Zeeuw, D., Toth, G., Collisionless Reconnection in Global Modeling of Magnetospheric Dynamics, 2006 Fall AGU Meeting, San Francisco, CA, December 11-15, 2006.

7. M.M. Kuznetsova, M. Hesse, L. Rastatter, G. T{\'o}th, D.L. DeZeeuw, T.I. Gombosi, Multi-Scale Modeling of Magnetospheric Reconnection, 2006 Spring AGU Meeting, Baltimore, MD, May 23-26, 2006.

8. M.M. Kuznetsova, M. Hesse, L. Rastatter, G. Toth, D.L. De Zeeuw, T.I. Gombosi, Multi-Scale Modeling of Magnetospheric Reconnection, 2006 Spring AGU Meeting, Baltimore, MD, May 23-26, 2006.

9. A. Taktakishvili, M. Kuznetsova, M. Hesse, L. Rastatter, G. Toth, D. De Zeeuw, T. Gombosi, Magnetotail Current Sheet Thinning in Global Simulations of Magnetosphere Dynamics, 2005 Fall AGU Meeting, San Francisco, CA, December 5-9, 2005.

10. M. M. Kuznetsova, M. Hesse, L. Rastatter, G. Toth, D. De Zeeuw, T. Gombosi, Magnetic Reconnection in Global MHD Modeling of Magnetosphere Dynamics, 2005 Fall AGU Meeting, San Francisco, CA, December 5-9, 2005.

11. M.M. Kuznetsova, Hesse, M., Rastaetter, L., Toth, G., De Zeeuw, D. L., Gombosi, T. I., Fast Magnetotail Reconnection: Challenge to Global MHD Modeling, 2005 Spring AGU Meeting, New Orleans, LA, May 23-27, 2005.

12. M.M. Kuznetsova, Hesse, M., Rastaetter, L., Gombosi, T. I., Intermittent Reconnection, Flux Ropes and Vortices Generation at the Dayside Magnetopause, 2004 Fall AGU Meeting, San Francisco, CA, December 13-17, 2004.